EFFICIENCY OF GAS TURBINE ENGINES FOR DRIVE OF MECHANISMS FOR IN-HOUSE NEEDS OF THERMAL POWER PLANTS[1,2]

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An equation is derived for determining the economic suitability, based on the period of return, of replacing an electrical drive mechanism for the in-house needs of a thermal power plant with a gas turbine engine as a function of the cost of electrical energy and fuel and the cost and performance of gas turbine engines.

Keywords: thermal power plants; mechanism for in-house needs; electric drive; steam turbine drive; gas turbine engine; payment period.

The production of electric power in modern power plants is entirely mechanized. The mechanisms for in-house needs are mainly driven by electricity, with steam-turbine energy only used for driving feed pumps and air blast in power generating units with supercritical pressure.

The fraction of electrical energy consumed in in-house needs of high-power thermal power plants with electrical drive for all the mechanisms is 6.0 – 7.5% for coal fired plants and 4.5 – 5.5% for gas and oil fired plants. Depending on the type of fuel and the type of turbines, the mechanisms of in-house needs at modern heating and electric power plants consume from 6.5 to 13% of the nominal power. Reducing the consumption of electric power on in-house needs is important for the operation, design, and modernization of thermal power plants and can be a significant saving of energy. Thus, using steam-turbine drive for feed pumps at supercritical power generating units has made it possible to reduce the amount of electrical energy for in-house needs by 2.0 – 2.5%.

Electrical drive in the form of asynchronous electric motors with a short-circuited rotor is most widespread use because of the following advantages:

— simplicity of construction, installation, and operation;

— possibility of manufacture at any nominal unit power; and,

— reliability of operation and the possibility of "self starting" after loss or a large drop in voltage in the electric grid.

But electric motors have a number of major disadvantages:

— low efficiency, given by the product of the efficiency with which electric power is generated (35 – 40%), the efficiency of electrical energy transport (95 – 98%), and the efficiency of the electric motor (90 – 96%), so that the overall efficiency does not exceed 30 – 35%;

— a constant rotation speed, which makes it difficult to control the capacity of mechanisms by changing the rotation frequency and leads to over expenditure on electric power for in-house needs of power plants in transitional modes; and,

— the difficulty of manufacturing high power motors and the large currents for starting them up.

The use of hydroclutches, regulated synchronous electric motors, or regulated frequency drive makes the drive much more costly and difficult to operate. The general disadvantages of electric drive include the need to install high-power transformers for in-house needs with a complex distribution system, high voltages (3 – 10 kV), and the possibility of high short-circuit currents during voltage losses in the supply grid.

With a steam-turbine drive it is possible to:

— provide ideal regulation of the capability of mechanisms by varying the rotation speed;

— provide mechanisms with a high rotation speed, so their performance is improved and their size and cost are lower;

— increase the useful release of electrical energy with the same turbine generator power through reducing the amount of electric drive;

— reduce expenses for the supply system for electric drive and decreasing the short-circuit currents; and,

— increase operational stability of the mechanisms as fluctuations in the current frequency do not affect their capacity.

The disadvantages of steam-turbine drives include:

— more complicated thermal configurations for a power production unit and power plant, and

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— the need to supply steam through a pipe from the startup boiler or through backup steam pipes from other generating units during startup of a power production unit or when its load is significantly reduced.

When the unit power of a steam turbine drive is low (usually less than 10 MW), its efficiency falls below that of an electric drive, and the cost of installing and operating it exceeds the cost of an electric drive; then it is inappropriate to replace an electric drive by a steam turbine drive.

The advantages of steam-turbine drive are also provided by a gas-turbine engine (GTE). Recently this type of engine has been under rapid development and even at low powers they already had efficiencies of 30 – 35% [1]. The advantage of a GTE is that the high temperature gases (450 – 550°C) emerging from it can be used in the steam turbine cycle in order to increase its efficiency or for increasing the output of heat to outside users. As a result, with a GTE it is possible to use up to 85% of the heat delivered to it, while a steam-turbine drive is limited to 35 – 40%.

Replacing an electric drive with a gas-turbine engine can also increase the electrical energy output of a thermal power station by the amount spent on the drive for the mechanism for in-house needs, and replacing it by a steam-turbine drive, by the amount of energy that was not generated by the main turbine because part of the steam is diverted through the piping. A GTE does not make the thermal circuit of a steam-gas unit more complicated and does not require steam for startup. One of the major advantages of GTE is their maneuverability. Thus, GTE based on aircraft engines can be started up and reach nominal power within 5 – 10 min. When necessary, a GTE can be started without electric power using starters based on compressed air or on gas.

Among the disadvantages of replacing an electric drive with a GTE is that capital investment is necessary for installing the new equipment and additional gas or liquid fuel is needed to run it.

One positive effect of replacing an electric drive with a gas-turbine engine occurs when the profit from selling the additional power generated by a steam turbine exceeds the capital cost of installing the new equipment and the cost of the fuel for the GTE.

Since an electric drive can be replaced by a GTE in 3 – 4 months, we estimate the economic effectiveness using a simple payment time for one-time capital costs without discounting [2],

$$T_{\text{pay}} = K/(\Delta P_{\text{net}} + \Delta U_{\text{am}}), \tag{1}$$

where K is the capital cost for purchase and installation of the GTE along with all of its auxiliary equipment; ΔP_{net} is the annual increment in net profit with replacement of an electric drive by a GTE; and, ΔU_{am} is the annual amortization deduction for the GTE and auxiliary equipment.

The capital cost of installing the GTE is defined as

$$K = k_{\text{GTE}} N_{\text{i.h.nom}} \eta_{\text{ed}}, \tag{2}$$

where k_{GTE} is the specific capital cost, rubles/kW, for purchase and installation of the GTE and the auxiliary equipment [booster compressors, air cleanup systems, air and gas lines for fuelling and exhaust, as well as heat exchangers for utilizing the heat in the exhaust gases (this indicator can include the additional expenses for backup equipment)]; $N_{\text{i.h.nom}}$ is the nominal power for the replaced electrical drive for the in-house needs, kW; and, η_{ed} is the efficiency of the electrical drive under nominal operation including losses in the transformer for in-house needs, the electrical grid, and the electric motor. (The efficiency of the electric drive is introduced in Eq. (2) because the power at the shaft for the mechanism for the in-house needs, which should be provided by the GTE, is less than $N_{\text{i.h.nom}}$ by an amount equal to the losses in the electric drive.)

The annual amortization deductions for the new equipment are given by

$$\Delta U_{\text{am}} = \alpha_{\text{am}} K, \tag{3}$$

where α_{am} is the fraction of amortization deductions.

The annual increment in the net profit when the GTE is installed is

$$\Delta P_{\text{net}} = \Delta P_{\text{b}} - \Delta H,$$

where ΔP_{b} is the annual increase in the balance receipts and ΔH is the tax on the income.

For a tax on the income of $\gamma = \Delta H/\Delta P_{\text{b}}$ we obtain

$$\Delta P_{\text{net}} = \Delta P_{\text{b}}(1 - \gamma). \tag{4}$$

The annual increment in the balance receipts is defined as

$$\Delta P_{\text{b}} = R_{\text{e}} - B_{\text{GTE}} C_{\text{f}}, \tag{5}$$

where R_{e} is the annual receipts from sale of the additional electrical energy, rubles; B_{GTE} is the flow rate of nominal fuel for the GTE, kg/year; and, C_{f} is the cost of the nominal fuel for the GTE, rubles/year.

The additional annual output of electrical energy is made up of the following components:

— an increase in electrical energy output by the amount of the decrease in its use for the mechanism for in-house needs with the GTE,

$$\Delta E_{\text{out1}} = N_{\text{i.h.y}} h_{\text{y}}, \tag{6}$$

where $N_{\text{i.h.y}}$ is the year-round load from the mechanism for in-house needs with an electrical drive, kW, and h_{y} is the number of hours the GTE operates per year;

— an increase in the electrical energy output by the amount of the reduction in power for controlling the operation of the mechanism for in-house needs by changing the rotation frequency,

$$\Delta E_{\text{out2}} = \Delta N_{\text{i.h.y}} h_{\text{y}}, \tag{7}$$

where $\Delta N_{\text{i.h.y}}$ is the year-round reduction in the power for the mechanism for in-house needs when its capacity is regulated by changing the rotation frequency, kW; and,

— an increase in the electrical energy output owing to the increase power of the main turbine when the heat of the exhaust gases from the GTE is used in the turbine cycle,

$$\Delta E_{\text{out3}} = Q_{\text{ex}} e \eta_{\text{em}} h_{\text{y}}, \tag{8}$$

where Q_{ex} is the usefully employed thermal power of the exhaust gases from the GTE, kW; e is the power utilization factor at the site where Q_{ex} is fed into the steam turbine cycle; and η_{em} is the electromechanical efficiency of the turbine generator.

Given Eqs. (6) – (8), the annual profit from selling the additional electrical energy is

$$R_{\text{e}} = (N_{\text{i.h.y}} + \Delta N_{\text{i.h.y}} + Q_{\text{ex}} e \eta_{\text{em}}) h_{\text{y}} C_{\text{e}}, \tag{9}$$

where C_{e} is the cost of the electrical energy output, rubles/(kW · h).

The annual fuel consumption by the GTE is given by

$$B_{\text{GTE}} = b_{\text{GTE}} N_{\text{i.h.y}} \eta_{\text{ed}} h_{\text{y}}, \tag{10}$$

where b_{GTE} is the specific nominal fuel supply rate to the GTE with $N_{\text{i.h.y}}$, kg/(kW · h).

Since $b_{\text{GTE}} = 0.123/\eta_{\text{GTE}}$, where η_{GTE} is the effective efficiency of the GTE with $N_{\text{i.h.y}}$, Eq. (10) can be rewritten in the form

$$B_{\text{GTE}} = 0.123 N_{\text{i.h.y}} \eta_{\text{ed}} h_{\text{y}}/\eta_{\text{GTE}}. \tag{11}$$

Equations (4), (9), and (11) then yield

$$\Delta P_{\text{net}} = [(N_{\text{i.h.y}} + \Delta N_{\text{i.h.y}} + Q_{\text{ex}} e \eta_{\text{em}}) h_{\text{y}} C_{\text{e}} - 0.123 N_{\text{i.h.y}} \eta_{\text{ed}} h_{\text{y}} C_{\text{f}}/\eta_{\text{GTE}}](1 - \gamma). \tag{12}$$

After substituting Eqs. (2), (3), and (12) in Eq. (1) and some simple calculations, we obtain

$$T_{\text{pay}} = \left\{ \left[\frac{N_{\text{i.h.y}} + \Delta N_{\text{i.h.y}}}{N_{\text{i.h.nom}}} \left(1 - \frac{0.123 \eta_{\text{ed}} C_{\text{f}}}{\eta_{\text{GTE}} C_{\text{e}}} \right) - \frac{Q_{\text{ex}}}{N_{\text{i.h.nom}}} e \eta_{\text{em}} \right] \frac{h_{\text{y}} (1-\gamma) C_{\text{e}}}{k_{\text{GTE}}} + \alpha_{\text{am}} \right\}^{-1}. \tag{13}$$

This equation can be transforms to a form that is more convenient for calculations and analysis.

We introduce the following notation: $k_{N_{\text{i.h}}} = N_{\text{i.h.y}}/N_{\text{i.h.nom}}$ is the annual load coefficient for the mechanism for in-house needs and $k_{\Delta N_{\text{i.h}}} = \Delta N_{\text{i.h.y}}/N_{\text{i.h.nom}}$ is a coefficient for the reduction in power consumption with regulation of the operation of the mechanism for in-house needs by changing the rotation frequency. The effective power of the GTE in the nominal operating mode can be written as $N_{\text{GTE.nom}} = Q_{\text{GTE.nom}} \eta_{\text{GTE.nom}} = N_{\text{i.h.nom}} \eta_{\text{ed}}$, where $Q_{\text{GTE.nom}}$ is the thermal power delivered to the GTE during nominal operation and $\eta_{\text{GTE.nom}}$ is the effective efficiency of the GTE during nominal operation. Then $N_{\text{i.h.nom}} = Q_{\text{GTE.nom}} \eta_{\text{GTE.nom}}/\eta_{\text{ed}}$. We introduce the ratio $k_{Q_{\text{ex}}} = Q_{\text{ex}}/Q_{\text{GTE.nom}}$ which is the utilization factor for the heat of the exhaust gases from the GTE.

Substituting these expressions in Eq. (13) gives

$$T_{\text{pay}} = \left\{ \left[(k_{N_{\text{i.h}}} + k_{\Delta N_{\text{i.h}}}) \left(1 - \frac{0.123 \eta_{\text{ed}} C_{\text{f}}}{\eta_{\text{GTE}} C_{\text{e}}} \right) + k_{Q_{\text{ex}}} \frac{e \eta_{\text{em}} \eta_{\text{ed}}}{\eta_{\text{GTE.nom}}} \right] \frac{h_{\text{y}} (1-\gamma) C_{\text{e}}}{k_{\text{GTE}}} - \alpha_{\text{am}} \right\}^{-1}. \tag{14}$$

Equation (14) can be used to analyze the effect of the primary operating and cost factors on the payment period to replace an electric drive with a gas-turbine engine for any mechanism for the in-house needs of a thermal power plant. It is clear that this period is determined by the cost of electrical energy and fuel, the specific capital expenses for the GTE, the effective efficiency of the GTE, the amount of time the drive works per year and its load coefficient, and the quality of and location at which the useable heat of the GTE exhaust gases is fed into the steam turbine cycle.

Equation (14) has been derived for the conditions under which thermal power plants are modernized, but it can also be used for evaluating the replacement of electric drive of the mechanisms for in-house needs by gas-turbine engine in newly designed and built thermal power plants. To do that, k_{GTE} must be replaced by the difference in the specific capital costs for a gas-turbine drive and an electrical drive.

In vital mechanisms for in-house needs requiring backup it is possible to retain backup mechanisms with electrical drive for rapid pickup of the load in case of an emergency shutdown of the GTE.

In order to get an idea of how C_{e}, C_{f}, and k_{GTE} affect the payment period for replacing an electric drive with a gas-turbine engine according to Eq. (14), calculations have been done for the following parameters: $h_{\text{y}} = 8500$ h; $k_{N_{\text{i.h}}} = 0.75$; $k_{\Delta N_{\text{i.h}}} = 0.2$; $k_{Q_{\text{ex}}} = 0.4$; $e = 0.3$; $\eta_{\text{ed}} = 0.95$; $\eta_{\text{em}} = 0.97$; $\eta_{\text{GTE.nom}} = 0.3$; $\eta_{\text{GTE}} = 0.25$; $\alpha_{\text{am}} = 0.083$; $\gamma = 0.2$. The results are shown in Table 1.

The data in Table 1 show that with increasing cost for gas turbine fuel and specific costs of the new equipment, the payment period rises rapidly. Thus, it is essential to consider variants for replacement of electric drive with a gas-turbine engine for gas-fired thermal power plants with gas firing of the GTE, and for high-power mechanisms for in-house needs with low specific capital costs for gas-turbine drive, such as feed, mains, and circulation pumps, as well as air blast, exhaust fans, and blower fans.

Recently there have been great advances in gas turbine technology (with increased efficiency at lower cost), so the prospects for their use as replacements for electrical drives of

TABLE 1

C_f, rubles/kg	k_{GTE}, rubles/kW	Payment period for replacement of electric drive (specific capital cost, in years) for C_e (rubles/kW · h)							
		0.50	0.75	1.00	1.25	1.50	1.75	2.00	3.00
1	5000	2.66	1.21	0.79	0.58	0.46	0.38	0.33	0.21
	10,000	4.36	2.20	1.48	1.11	0.89	0.74	0.64	0.40
	15,000	5.54	3.03	2.09	1.59	1.28	1.08	0.93	0.60
	20,000	6.40	3.73	2.63	2.03	1.65	1.40	1.48	0.78
	25,000	7.06	4.32	3.12	2.44	2.00	1.70	1.21	0.96
2	5000	—	4.54	1.50	0.90	0.64	0.50	0.41	0.24
	10,000	—	6.60	2.66	1.67	1.21	0.95	0.79	0.46
	15,000	—	7.77	3.59	2.34	1.73	1.38	1.14	0.68
	20,000	—	8.52	4.36	2.93	2.20	1.77	1.48	0.89
	25,000	—	9.05	5.00	3.45	2.64	2.13	1.79	1.09
3	5000	—	—	15.47	1.95	0.90	0.64	0.54	0.27
	10,000	—	—	13.55	3.36	1.92	1.34	1.03	0.54
	15,000	—	—	13.01	4.42	2.66	1.90	1.48	0.79
	20,000	—	—	12.75	5.25	3.50	2.41	1.90	1.03
	25,000	—	—	12.61	5.92	3.87	2.87	2.28	1.26
5	5000	—	—	—	—	—	4.95	1.54	0.41
	10,000	—	—	—	—	—	7.02	2.73	0.79
	15,000	—	—	—	—	—	8.16	3.68	1.15
	20,000	—	—	—	—	—	8.87	4.45	1.49
	25,000	—	—	—	—	—	9.37	5.09	1.80

Note. Table entries with a dash correspond to a negative effect from installation of a gas-turbine drive.

the mechanisms for in-house needs of thermal power plants are improved.

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